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CHARGE-TRANSFER-BASED SIGNAL INTERFACE FOR DIFFERENTIAL CAPACITIVE SENSORS

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Abstract – We propose a circuit to directly connect a differential capacitive sensor to a microcontroller unit (MCU), which is based on the charge-transfer method and does not need any calibration component. The performance has been tested by emulating the differential capacitive sensor with discrete components. The major uncertainty sources are residual stray capacitances. The maximal deviation obtained, referred to the Full Scale Span (FSS), is ±4 % for sensors with nominal capacitance C_0 = 100 pF, and ±0,6 % for sensors with C_0 = 1 nF.

Keywords: Differential capacitive sensor, charge transfer, sensor-to-microcontroller interface, direct sensor interface

1. BASIC INFORMATION

Differential capacitive sensors are widely used to measure linear or angular position and displacement, pressure, force, and acceleration, as described, for example, in [1]–[4]. Their electrical model are two sensing capacitances (i.e. C_1 and C_2) with a movable common electrode (C), as shown in Fig 1, whose values change with respect to the physical quantity being sensed in equal proportion but in opposite directions.

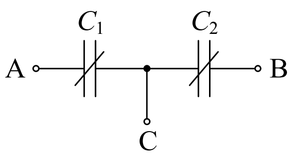

Fig. 1. Equivalent circuit of a differential capacitive sensor.

Depending on the effect of the movement of C, the change in the sensor’s capacitances C_1 and C_2 has a linear or hyperbolic characteristic that can be expressed by [5],

$$C_1 = C_0\left(1+x\right),\ C_2 = C_0\left(1-x\right) \tag{1}$$

$$C_1 = \frac{C_0}{1-x},\ C_2 = \frac{C_0}{1+x} \tag{2}$$

where C_0 is the resting value of C_1 and C_2 and x is the relative change of capacitance, hence $-1 < x < +1$. In both cases, x can be calculated from

$$x = \frac{C_1 - C_2}{C_1 + C_2} \tag{3}$$

Signal interfaces for capacitive sensors are usually based on voltage divider circuits and derivatives thereof such as dc bridges and pseudo-bridges, or on sinusoidal or relaxation oscillators [6]–[9]. These circuits rely on either analogue components and analogue-to-digital converters (ADC) or time/frequency measurements [8], [9]. Usually, the resulting signal is acquired, stored, processed, displayed and/or communicated to other devices or systems via a digital unit (e.g., a MCU). This measurement chain is implemented in some commercial integrated circuits (ICs) that integrate, for example, the signal conditioning circuit, the ADC and/or MCU, such as AD7745 (Analog Devices), ZSSC3122 (ZMDI), MS3110 (Irvine Sensors), or the oscillator, such as UTI (Smartec). Overall, the number of components in discrete solutions or the use of specialized ICs with no second source supplier available hinders the design of cost-effective solutions based on these approaches.

Differential capacitive sensors can be measured by a MCU as single active component [4], [10]. The MCU measures the time interval needed to discharge the sensors to a given threshold voltage through a reference resistor R_r, without any intermediate electronics. Hence, these interface circuits are cost-effective solutions because only the sensor and a MCU are required. Nevertheless, to obtain the best speed–accuracy trade off when measuring capacitances on the order of 100 pF, they need R_r > 20 MΩ, which may increase electronic noise and external interference (EMI).

Here we propose a direct interface circuit based on the charge-transfer method, where the unknown capacitance is calculated by counting the number of charge-transfer cycles needed to charge a reference capacitor to a threshold voltage via the capacitive sensor. In contrast with [4] and [10], the circuit does not include any large resistor hence its susceptibility to noise and EMI should be lower. Furthermore, the MCU does not need to include even a timer. The charge-transfer-based method is used in switched capacitor circuits that implement resistances in ICs [11] and have good ability to reject external EMI. In a previous work [12], we analysed the susceptibility of these circuits for single capacitive sensors to uncertainty sources such as stray capacitance and temperature and power supply voltage drifts, and proposed design solutions to reduce their effect. This paper extends that analysis to differential capacitive sensors with values from 100 pF to 1 nF, considers the limitations when stray capacitances are accounted for, and proposes novel measurement methods to overcome them.